Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 00 (2015) 000–000

www.elsevier.com/locate/procedia

The 22nd CIRP conference on Life Cycle Engineering

Environmental comparison of metal coating processes

Karel Kellens[a]*, Dimos Paraskevas[a], Wim Dewulf[a,b], Joost R. Duflou[a]

[a] *Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, 3000 Leuven, Belgium*
[b] *Mechanical Engineering Technology TC, Campus Leuven (@GroupT), Andreas Vesaliusstraat 13, 3000 Leuven, Belgium*

* Corresponding author. Tel.: +32-16-322499; fax: +32-16-322986. *E-mail address:* Karel.Kellens@kuleuven.be

Abstract

Taking into account the expected growth of the world's population and increasing welfare level in developing countries, the global energy and material resource demand can be expected to increase significantly. Therefore, the environmental burden per unit produced should be strongly reduced in order to assure a sustainable impact level [1-2]. This paper describes the environmental assessment and comparison of two alternative metal coating techniques: i.e. electrostatic powder coating and fluidized bed sintering. The paper starts with a general description of both investigated metal coating processes. Subsequently the life cycle inventory data collection effort is described and an environmental impact assessment is performed for both processes. The environmental performance of both processes is compared taking into account the differences in expected life time of both coatings. Finally, an overview of potential improvement measures is provided.

Peer-review under responsibility of the International Scientific Committee of the Conference "22nd CIRP conference on Life Cycle Engineering.

Keywords: Environmental Assessment; Metal Coating Processes, Sustainable Production

1. Introduction

Due to increasing energy and resource costs on the one hand and upcoming regulations on energy and resource efficiency on the other, a growing interest of machine tool builders in the environmental performance of their machine tools can be observed today. The last decade, academic as well as industrial research groups started to assess the environmental aspects of discrete part manufacturing processes and indicated a significant potential for improvement [3].

Among others, Papasavva et al. [4] and DSM [5] indicated that the transition of solvent-based coatings to water-based and powder based coatings leads to a significant improvement of the environmental performance of painting and coating processes. However, only few quantitative environmental analyses are available for powder coating processes today.

This paper describes the environmental assessment of two alternative metal coating processes: i.e. electrostatic powder coating of 150µm TGIC-free polyester powder and fluidized bed sintering of 250µm PVC powder. The main part of this research was carried out as part of the master thesis of Lionel Thienpont [6].

2. Process description

This section provides a general description of both analysed metal coating processes: electrostatic powder coating (Figure 1) and fluidized bed sintering (Figure 2).

2.1. Electrostatic powder coating

Chemical pretreatment: The first step is the chemical pretreatment of the steel surface to assure the surface is free of corrosion and grease, which in turn will assure a uniform and permanent adhesion of the coating [7]. The second function of the chemical pretreatment is the application of a zinc conversion layer which is the basis for the primary polyester coating. Stringent process control is crucial to meet the high quality standards. The pretreatment consists of a series of baths. The first bath is the degreasing bath where the surface of the workpiece is treated with an aqueous solution of organic and inorganic salts at 50°C. The solution is sprayed upon the workpiece and rinsed in the subsequent bath. The following step is the pickling bath where oxide films, flakes and other corrosion products of the metal are removed. A reaction takes place between the metal oxide and the acid solution resulting in a metal ion and water. After the pickling bath the workpiece is rinsed and transported to the phosphating bath. Phosphating is a chemical process where an insoluble phosphate film is formed on the metal surface. Before the conversion layer can be applied, the surface must be activated with an aqueous solution of alkali salts including titanium salt. Activating the surface increases the number of crystals per unit surface by which the crystal size, coating weight and reaction time is reduced [8]. The activation sites react with the tricationic zinc phosphate forming the conversion layer at a temperature of 50°C. The quality of the conversion layer strongly depends on the crystal size and coating weight. After the coating is formed the surface is passivized. A passivation layer is created that prevents oxidation and enhances the adhesion of the subsequent coating. While the workpiece is rinsed between every chemical step, a final rinse with demineralized water takes place after the passivation step. The concentration baths are emptied periodically by an independent company which processes the sludge remaining in the baths. Finally, the workpiece is dried in a drying oven.

Powder deposition: After the chemical pretreatment the powder is deposited onto the workpiece. The analysed powder is TGIC-free polyester powder. This powder is deposited on the workpiece by electrostatic spraying guns. Compressed air is blown through the powder reservoir resulting in a fluidized powder movement. The powder gains a positive electric charge at the gun tip due to highly negative potential electrodes. The air around the gun tip becomes conductive and a corona field is formed. A loaded powder mist is formed in the area between the gun tip and the grounded workpiece. The electrical field ensures the trajectory of the powder mist from the gun tip to the workpiece [9]. This ensures that the powder is deposited very efficiently on the workpiece.

Curing: Finally, the workpiece is transported to the curing oven which consists of two zones operating at 190°C and 200°C respectively. The polyester coating is hardened by crosslinking of the polymer.

2.2. Fluidized bed sintering

The main principle of fluidized bed sintering is the immersion of a preheated workpiece in a fluidized bed of thermoplastic powder, in this case polyvinylchloride (PVC).

Deposition of primer: The process starts with the deposition of a corrosion resistant epoxy-acrylate primer facilitating the adhesion of the primary PVC coating. Since the primer is a waterborne paint, no solvents are used avoiding volatile organic compound (VOC) emissions.

Immersing in fluidized bed: The workpiece is preheated to 350°C and subsequently immersed in a fluidized bed containing PVC powder particles. The particles are fluidized by blowing compressed air through a porous membrane. The fluidized powder particles melt on the heated surface. The obtained coating thickness depends on the preheating temperature, heat capacity of the workpiece as well as the residence time in the fluidized bed [10]. To ensure that the powder particles completely melt on the surface, the workpiece can be reheated. The powder used is bulk polymerized polyvinylchloride mixed with a DINP-plasticizer (25%) and other additives such as, for example, the pigment.

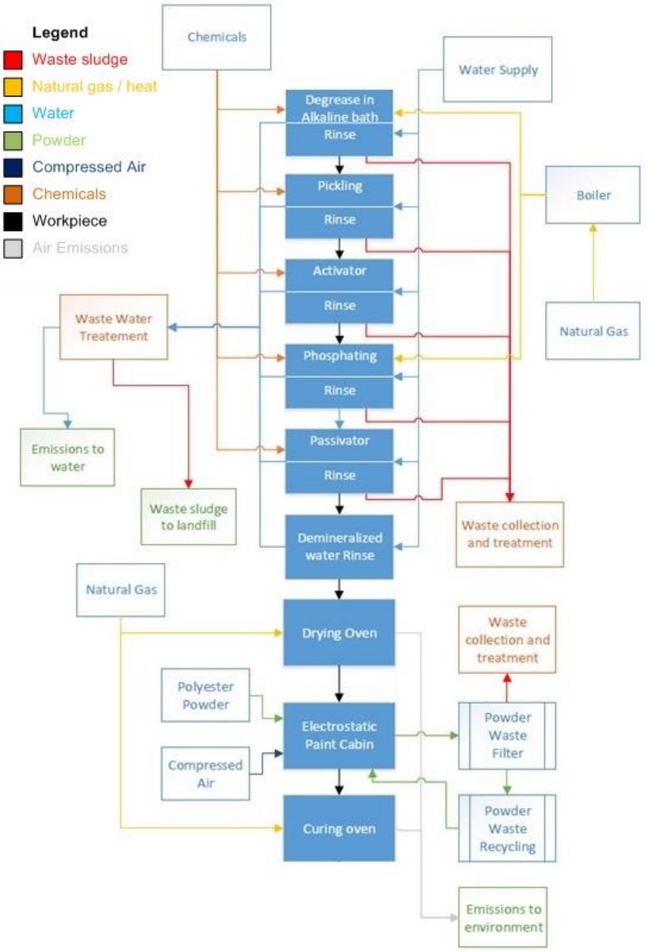


Fig. 1. Flow chart of electrostatic powder coating process.

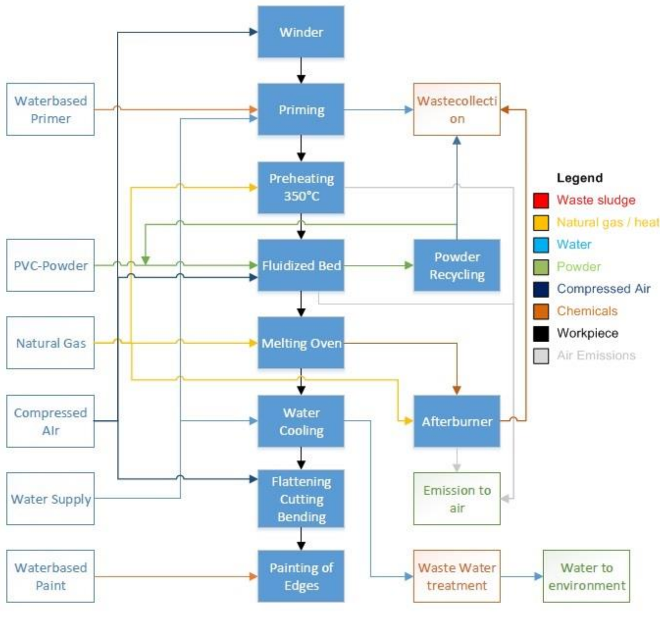


Fig. 2. Flow chart of fluidized bed sintering process.

Afterburning of plasticizer: When the powder particles melt on the workpiece surface a part of the plasticizer evaporates causing a pungent smell. In order to prevent this smell, the evaporated plasticizer is burned in an afterburner.

Cooling: Once the powder particles are completely melted, the coating is hardened by spraying cooling water onto the workpiece. The cooling water is collected and re-used in an internal circuit that is refreshed periodically.

Finishing: Finally, the workpiece is cut, flattened and/or bent. Since they are no longer protected, the cutted edges are recoated with a water based acrylate paint.

3. Environmental impact assessment

3.1. Goal and scope definition

Goal of the study: The goal of the study is to quantify the environmental impact caused during the coating of metal surfaces by electrostatic powder coating and fluidized bed sintering processes. The applied coatings are respectively 150µm TGIC-free polyester (PES) and 250µm polyvinylchloride (PVC). Both alternative coatings provide a similar coating resistance. The difference in coating thickness can be explained by the grain size of the powder materials as well as technological constraints.

System boundaries: The system boundaries of the assessment for both investigated coating processes cover the energy and resource demand as well as direct process emissions caused during the operating phase of all sub-processes (see Figures 1 and 2). The production and end-of-life treatment of the production line itself are not included.

Functional unit: The functional unit of the environmental impact assessment is set to one square meter (m²) of coated surface.

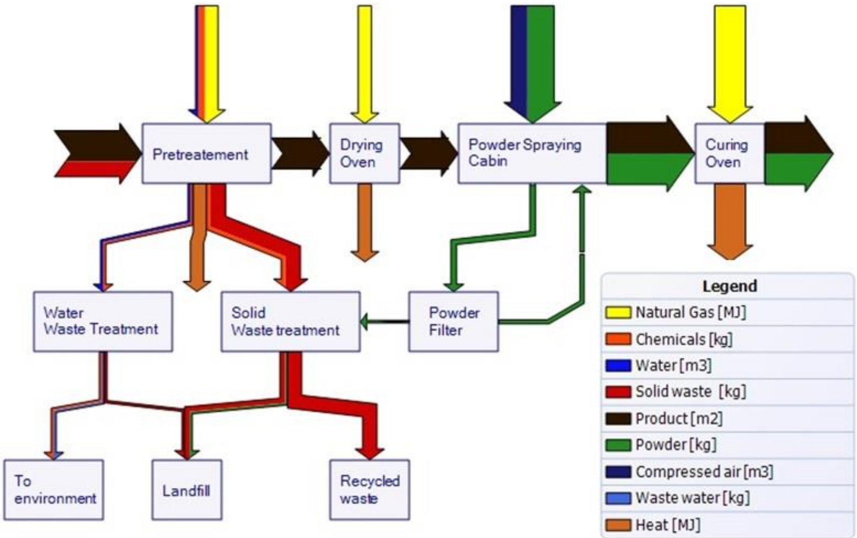


Fig. 3. Sankey diagram of electrostatic powder coating process.

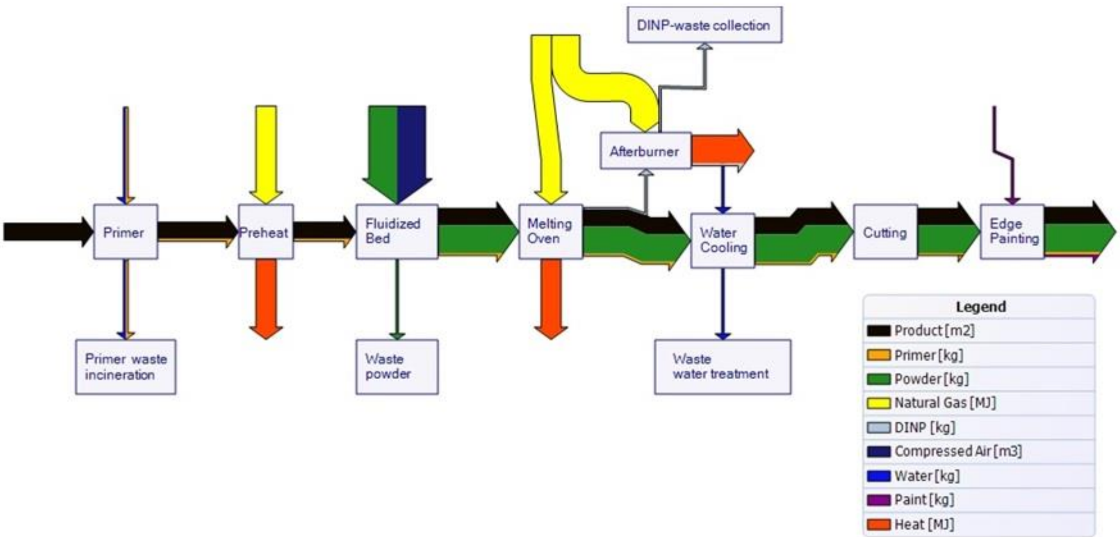


Fig. 4. Sankey diagram of fluidized bed sintering process.

3.2. LCI data collection

This section describes the results of the life cycle inventory (LCI) data collection effort which was performed in close collaboration with a large metal coating company (Betafence). The collected data covers all relevant energy and resource consumption as well as direct process emissions over a production period of 1 year in which a wide range of products have been processed. The gathered data is obtained by process measurements as well as from company data and extended with data from literature where required. All datasets are modelled using initial LCI records from the EcoInvent 2.2 database [11].

Taking into account the confidentiality of some of the datasets, the raw data values are not provided but presented as Sankey diagrams in Figures 3 and 4 respectively. Since the electricity is measured over the entire production line, it's not mentioned in the Sankey diagrams. The electricity demand per m² of coated surface is 0,764kWh and 0,420kWh respectively.

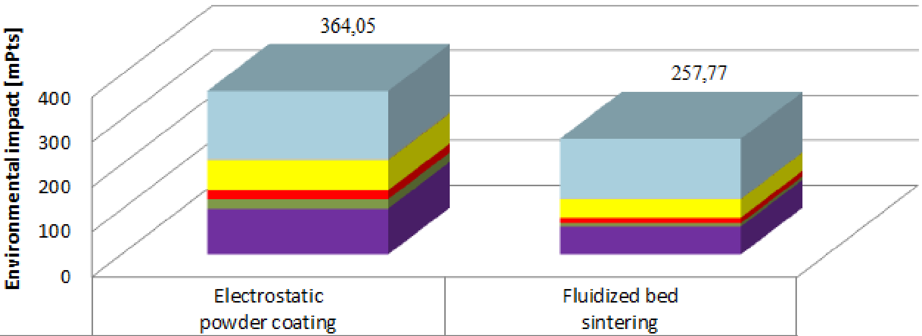
The specific chemicals were gathered from the relevant material safety data sheets (MSDSs). Direct air emissions (e.g. CO, NOx, SO2, TOC, VOC…) were quantified by chemical analyses (e.g. gas chromatography…) of air samples taken just after the exhaust filter or based on available LCI-data from Ecoinvent 2.2 [11]. The DINP plasticizer was modelled based on data from [12] and [13]. The sludge from the concentration baths (degreasing, pickling, activation, phosphating and passivation) is recycled. Incineration is applied as end-of-life treatment for solid waste streams.

3.3. Impact assessment

Using the Europe ReCiPe H/A life cycle impact assessment method [14], the environmental impact of both processes has been quantified at mid- as well as endpoint level. Figure 5 provides for both investigated processes the single score environmental impact per square meter of coated surface as well as the impacts at midpoint level. Only looking at the production phase (e.g. coating step), the impact of electrostatic powder coating of 150µm PES is 41,6% larger compared to fluidized bed sintering of 250µm PVC.

For both processes the main midpoint impact categories are fossil depletion, climate change ecosystems, particulate matter formation, human toxicity and climate change human health.

Figures 6 and 7 show the main contributors to the environmental impact for both processes. With respectively 52,76% and 70,06%, the powder consumption causes the largest part of the impact. Further relevant contributors are the consumption of natural gas, electricity and compressed air.



	Electrostatic powder coating	Fluidized bed sintering
Fossil depletion	150,14	133,32
Metal depletion	0,17	0,05
Natural land transformation	1,53	0,95
Urban land occupation	0,48	0,17
Agricultural land occupation	1,49	0,29
Marine ecotoxicity	0,00	0,00
Freshwater ecotoxicity	0,02	0,01
Terrestrial ecotoxicity	0,08	0,04
Freshwater eutrophication	0,14	0,05
Terrestrial acidification	0,14	0,09
Climate change Ecosystems	66,73	40,60
Ionising radiation	0,43	0,18
Particulate matter formation	19,86	12,52
Photochemical oxidant formation	0,01	0,01
Human toxicity	20,75	7,39
Ozone depletion	0,02	0,01
Climate change Human Health	102,05	62,09

Fig. 5. Environmental impact per square meter of coated surface.

Peer-review under responsibility of the International Scientific Committee of the Conference "22nd CIRP conference on Life Cycle Engineering.

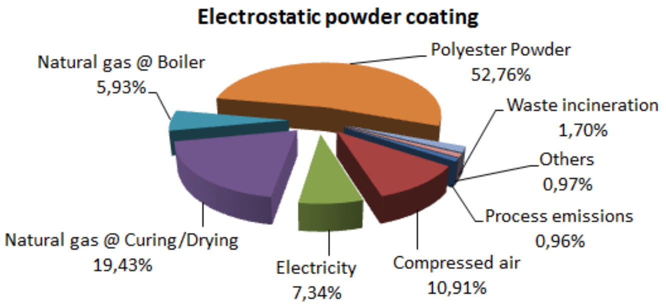


Fig. 6. Impact distribution for electrostatic powder coating

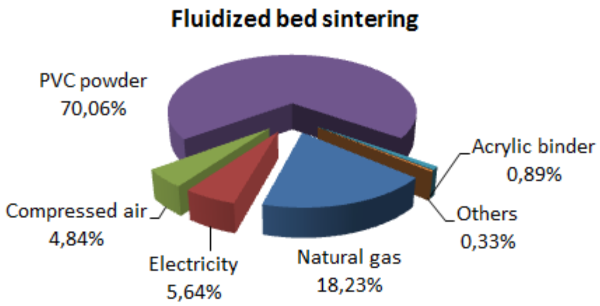


Fig. 7. Impact distribution for fluidized bed sintering

3.4. Environmental comparison of both processes

In order to make an appropriate comparison between the investigated processes, the expected lifetime of both coatings should be taken into account. In consequence the functional unit to compare both processes is adjusted to one square meter (m^2) coated surface per year of corrosion resistance (warranty). The end-of-life treatment of the coatings and products (e.g. recoating, incineration…) are outside the scope of this study.

Based on industrial experiences and in line with the offered product warranties, the corrosion resistance of the PVC-coating outlasts this of the PES-coating. The estimated lifetime for both coatings is 30 and 20 years respectively.

As shown in Figure 8, the quantified environmental impact of the analysed electrostatic powder coating process (18,20 mPts) is approximately twice as high as this of fluidized bed sintering alternative (8,59 mPts).

3.5. Sensitivity analysis

In order to check the accuracy of the obtained results, sensitivity analyses have been performed for the most important energy and resource flows of both investigated processes.

For the electrostatic powder coating process, a variation of 10% in PES powder consumption (e.g. applied layer thickness) has an influence of 5,3% on the total environmental impact. A variation of 20% in natural gas, electricity or compressed air consumption leads to a difference in environmental impact of 5,1; 1,5 and 2,2% respectively.

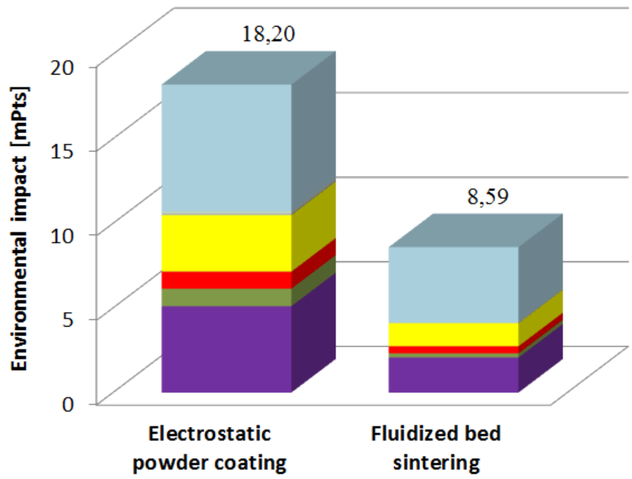


Fig. 8. Environmental impact per m² coated surface per year of corrosion resistance.

For the fluidized bed sintering process, a variation of 10% in PVC powder consumption (e.g. applied layer thickness) or natural gas consumption have an influence of respectively 7,1% and 1,8% on the total environmental impact.

The main uncertainty in the composition of the PVC powder is the weight percent of the pigment. While the weight percent of the DINP plasticizer is kept constant, the weight percent of the bulk PVC powder is adjusted accordingly. A variation of 10% in weight percent of the pigment leads to a change in total environmental impact of approximately 4,9%.

4. Potential improvement measures

This section provides a preliminary overview of potential environmental improvement measures for both processes. However, further identification, investigation, and quantification of these potential improvement measures is required.

A first general observation for both processes is that the applied layer thicknesses (and thus powder volume) is usually larger than the required value. Taking into account the major contribution of the powder materials to the total environmental impact (see Figures 6 and 7), optimized process control will provide significant benefits from economic as well as environmental perspective.

Since the investigated coating processes need both electricity and heat, cogeneration or combined heat and power (CHP) [15] could be applied in order to improve the efficiency of energy production and reduce the related environmental impact.

Specific improvement measures for each of both coating processes are listed in the next two sections.

4.1. Electrostatic powder coating

- The production speed depends on the type of product to be coated. In consequence some production parameters, such as the compressed air flow during powder spraying and the temperature of the curing oven are variable. Better control of these process parameters will optimize (reduce) the related energy and resource demand.
- The water consumption is already limited by the applied spraying technique. However, regeneration (e.g. ion exchangers, reverse osmosis) and re-use of the rising water could further reduce the water demand.
- Replacement of the currently used conventional convection ovens by infrared radiation ovens would have multiple benefits: fast curing of coating without heating the workpiece itself; no air movements and related potential for disturbance of the coating; and reduced dwell time.
- Substitution of the epoxy-based coating powders by a polyester-based alternative (as applied in this study) reduces the occupational health risk for workers as well as other environmental impacts [16].
- Currently, new powder materials are under development which would require less coating thicknesses and/or lower curing temperatures.

4.2. Fluidized bed sintering

- After leaving the melting oven, the workpieces are cooled by a closed water circuit. The waste heat of the involved heat exchanger can be recovered and used for heating the degreasing and phosphating baths.
- Around 70% of the total environmental impact is caused by the production of the applied PVC powder. The PVC powder could be substituted by a more environmental friendly alternative such as polyethylene. Since polyethylene doesn't contain phthalates, no evaporation of the plasticizer occurs and there is no need for an afterburner. In consequence the natural gas consumption could be reduced by approximately 30%.

While the first improvement actions (e.g. better control of the process parameters…) are initiated within the involved company, quantification of the obtained results is expected for the second or third quarter of 2015.

5. Conclusions

This paper provides an environmental assessment of two alternative metal coating processes. Neglecting the impact of the production as well as end-of-life treatment of the coating lines itself, the quantified environmental impact of the investigated electrostatic powder coating (150µm PES) and fluidized bed sintering (250µm PVC) processes are 364,05 and 257,77mPts per coated surface of one square meter.

Taking into account the protective life time of both coatings, the environmental impact of the PES coating is approximately twice the impact caused by the PVC coating.

Finally, potential environmental improvement measures are listed and include process control measures, technology changes as well as development and application of alternative powder materials.

Future work includes further identification, implementation and quantification of the environmental improvements for both metal coating processes.

Acknowledgements

The authors wish to thank Lionel Thienpont, graduated master student at the Department of Mechanical Engineering, KU Leuven as well as industrial partner Betafence for their contributions to this research.

References

[1] Rahimifard S., Sheldrick L., Woolley E., Colwill J., Sachidanandra M. How to Manufacture a Sustainable Future for 9 Billion People in 2050. Proceedings of the 20th Int. CIRP Conference on Life Cycle Engineering, Singapore, Re-engineering Manufacturing for Sustainability, 2013, 1-8.
[2] Dornfeld D. Green Manufacturing, Springer. New York Heidelberg Dordrecht London, 2013, ISBN: 978-1-4419-6015-3.
[3] Duflou J.R., Sutherland J.W., Dornfeld D., Herrmann C., Jeswiet J., Kara S., Hauschild M., Kellens K.. Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals – Manufacturing Technology, 2012, 61/2:587-609.
[4] Papasavva S., Kia S., Claya J., Gunther, R., Life cycle environmental assessment of paint processes. Journal of Coatings Technology, 2002, 74/925:65-76.
[5] DSM, Carbon Footprint Study for Industrial Coatings Applied on a Metal Substrate: Focus on Powder Coatings, 2011, DSM Coating Resins, www.dsmcoatingresins.com
[6] Thienpont L., Environmental comparison of metal coating technologies. Master thesis, 2014, Department of Mechanical Engineering, KU Leuven.
[7] European Commission, Integrated Pollution Prevention and Control: Best Available Techniques Reference Document for the Surface Treatment of Metals and Plastics, 2006,. http://eippcb.jrc.ec.europa.eu/reference.
[8] Wolpers M., Angeli J., Activation of galvanized steel surfaces before zinc phosphating — XPS and GDOES investigations. Applied Surface Science, , 2001, 179:281-291.
[9] Bailey A., The science and technology of electrostatic powder spraying, transport and coating. Journal of Electrostatics, 1998, 45/2: 85-120
[10] Misve T.A., Powder coatings: chemistry and technology. Chichester: Wiley, 1991, 379 p. ISBN:0-471-92821-6.
[11] Ecoinvent Centre, Swiss Centre for Life Cycle Inventories, ecoinvent database v2.2,2013, available online: http://www.ecoinvent.ch
[12] Van der Klis T., Vademecum oppervlaktetechnieken metalen, Bilthoven: Vereniging voor Oppervlaktetechnieken van Materialen, 1989, 711 p.
[13] European Commision. The international reference life cycle data system (ILCD) handbook, EC Joint Research Center – Institute for Environment and Sustainability, 2012, ISBN: 987-92-79-21640-4.
[14] Goedkoop M., Heijungs R., Huijbregts M., De Schryver A., Struijs J., Van Zelm R. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, First edition (revised) Report I: Characterisation, 2013, available online: http://www.lcia-recipe.net
[15] Cogen Europe, the European Association for the promotion of Cogeneration , http://www.cogeneurope.eu
[16] Askham C. Environmental product development: replacement of an epoxy-based coating by a polyester-based coating, International Journal of Life Cycle Assessment, 2011, 16:819-828.